

Particle Dark Matter in DAMA/LIBRA

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Abstract

The present DAMA/LIBRA experiment and the former DAMA/NaI have cumulatively released so far the results obtained with the data collected over 13 annual cycles (total exposure: $1.17 \text{ ton} \times \text{yr}$). They give a model independent evidence of the presence of DM particles in the galactic halo on the basis of the DM annual modulation signature at 8.9σ C.L. for the cumulative exposure.

1 Introduction

The DAMA project is based on the development and use of low background scintillators, and several low background set-ups have been realized and used for various kinds of investigations [1]. In particular, the former DAMA/NaI and the present DAMA/LIBRA experiments at the Gran Sasso National

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Laboratory of the INFN have the main aim to investigate the presence of Dark Matter particles in the galactic halo by exploiting the model independent DM annual modulation signature, originally suggested in the mid 80's in ref. [2]. In fact, as a consequence of its annual revolution around the Sun, which is moving in the Galaxy travelling with respect to the Local Standard of Rest towards the star Vega near the constellation of Hercules, the Earth should be crossed by a larger flux of Dark Matter particles around ~ 2 June (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around ~ 2 December (when the two velocities are subtracted). It is worth noting that this signature has a different origin and peculiarities than the seasons on the Earth and than effects correlated with seasons (consider the expected value of the phase as well as the other requirements listed below). This annual modulation signature is very distinctive since the effect induced by DM particles must simultaneously satisfy all the following requirements: the rate must contain a component modulated according to a cosine function (1) with one year period (2) and a phase that peaks roughly around $\simeq 2^{nd}$ June (3); this modulation must only be found in a well-defined low energy range, where DM particle induced events can be present (4); it must apply only to those events in which just one detector of many actually “fires” (*single-hit* events), since the DM particle multi-interaction probability is negligible (5); the modulation amplitude in the region of maximal sensitivity must be $\lesssim 7\%$ for usually adopted halo distributions (6), but it can be larger in case of some possible scenarios such as e.g. those in refs. [3, 4]. This offers an efficient DM model independent signature, able to test a large interval of cross sections and of halo densities; moreover, the use of highly radiopure NaI(Tl) scintillators as target-detectors assures sensitivity to wide ranges of DM candidates, of interaction types and of astrophysical scenarios.

It is worth noting that only systematic effects or side reactions able to simultaneously fulfil all the requirements given above (and no one has ever been suggested over more than a decade) and to account for the whole observed modulation amplitude might mimic this DM signature.

The description, radiopurity and main features of the DAMA/LIBRA set-up are discussed in details in ref. [5, 6]; moreover, this set-up has firstly been upgraded in September/October 2008 [7].

The cumulative DAMA/LIBRA exposure – after the new data release occurred at beginning of 2010 [7] – is $0.87 \text{ ton} \times \text{yr}$ (6 annual cycles), and cumulatively with DAMA/NaI the exposure is $1.17 \text{ ton} \times \text{yr}$ (13 annual cycles in total).

2 The model independent result

Several analyses on the model-independent investigation of the DM annual modulation signature have been performed in [7] as previously done in ref.

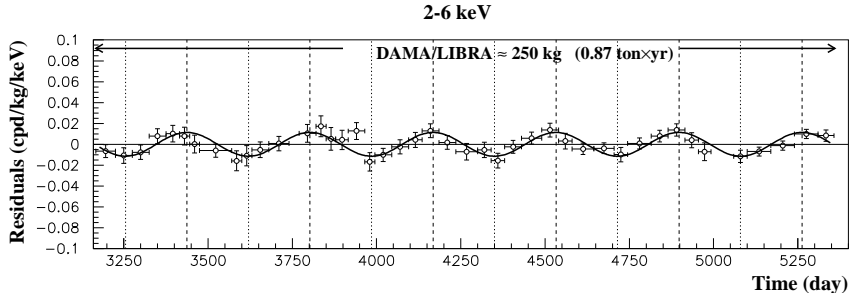


Figure 1: Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/LIBRA-1,2,3,4,5,6 in the (2 – 6) keV energy interval as a function of the time [6, 7]. The zero of the time scale is January 1st of the first year of data taking of the former DAMA/NaI experiment. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve is the cosinusoidal function behavior $A \cos \omega(t - t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, with a phase $t_0 = 152.5$ day (June 2nd) and with modulation amplitude, A , equal to the central value obtained by best fit over the whole data including also the exposure previously collected by the former DAMA/NaI experiment. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2nd), while the dotted vertical lines correspond to the minimum. See refs. [6, 7] and refs. therein.

[6] and refs. therein. In particular, Fig. 1 shows the time behaviour of the experimental residual rates for *single-hit* events in the (2–6) keV energy interval; as known, here and hereafter keV means keV electron equivalent. The hypothesis of absence of modulation in the data can be discarded [6, 7]. Moreover, when the period and the phase parameters as well as the modulation amplitude are kept free fitting the experimental residuals of Fig. 1 with the formula: $A \cos \omega(t - t_0)$, values well compatible with the expectations for a signal in the DM annual modulation signature are found [6, 7]. In particular, the phase – whose better determination is obtained by using a maximum likelihood analysis [6, 7] – is consistent with about June 2nd within 2σ . For completeness, we note that a slight energy dependence of the phase could be expected in case of possible contributions of non-thermalized DM components to the galactic halo, such as e.g. the SagDEG stream [8] and the caustics [9].

The data have also been investigated by a Fourier analysis, obtaining a clear peak corresponding to a period of 1 year; the same analysis in other energy region shows instead only aliasing peaks [6, 7].

The measured energy distribution has been investigated in other energy regions not of interest for Dark Matter, also verifying the absence of any significant background modulation². In particular, the measured rate integrated above 90 keV, R_{90} , as a function of the time has been analysed; fitting its time behaviour with phase and period as for DM particles, a modulation amplitude compatible with zero is found excluding the presence of any background modulation in the whole energy spectrum at a level much lower than the effect found in the lowest energy region for the *single-hit* events [6, 7]. Similar result is obtained when comparing the *single-hit* residuals in the (2–6) keV with those in other energy intervals [6, 7]. It is worth noting that the obtained results already account for whatever kind of background and, in addition, that no background process able to mimic the DM annual modulation signature (that is able to simultaneously satisfy all the peculiarities of the signature and to account for the measured modulation amplitude) is available (see also discussions e.g. in [6, 10], refs. therein and later).

A further relevant investigation has been performed by applying the same hardware and software procedures, used to acquire and to analyse the *single-hit* residual rate, to the *multiple-hit* one. In fact, since the probability that a DM particle interacts in more than one detector is negligible, a DM signal can be present just in the *single-hit* residual rate. Thus, the comparison of the results of the *single-hit* events with those of the *multiple-hit* ones corresponds practically to compare between them the cases of DM particles beam-on and beam-off. This procedure also allows an additional test of the background behaviour in the same energy interval where the positive effect is observed. In particular, in Fig. 2 the residual rates of the *single-hit* events measured over the six DAMA/LIBRA annual cycles are reported, as collected in a single cycle, together with the residual rates of the *multiple-hit* events, in the considered energy interval. While, as already observed, a clear modulation, satisfying all the peculiarities of the DM annual modulation signature, is present in the *single-hit* events, the fitted modulation amplitude for the *multiple-hit* residual rate is well compatible with zero [7]. Thus, again evidence of annual modulation with proper features as required by the DM annual modulation signature is present in the *single-hit* residuals (events

²In fact, the background in the lowest energy region is essentially due to “Compton” electrons, X-rays and/or Auger electrons, muon induced events, etc., which are strictly correlated with the events in the higher energy part of the spectrum. Thus, if a modulation detected in the lowest energy region would be due to a modulation of the background (rather than to a signal), an equal or larger modulation in the higher energy regions should be present.

class to which the DM particle induced events belong), while it is absent in the *multiple-hit* residual rate (event class to which only background events belong). Since the same identical hardware and the same identical software procedures have been used to analyse the two classes of events, the obtained result offers an additional strong support for the presence of a DM particle component in the galactic halo.

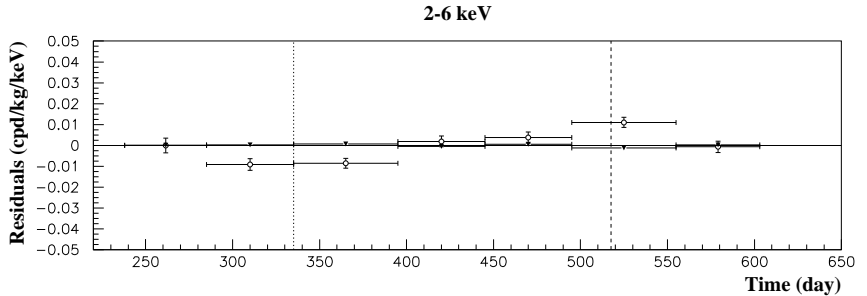


Figure 2: Experimental residual rates over the six DAMA/LIBRA annual cycles for *single-hit* events (open circles) (class of events to which DM events belong) and for *multiple-hit* events (filled triangles) (class of events to which DM events do not belong). They have been obtained by considering for each class of events the data as collected in a single annual cycle and by using in both cases the same identical hardware and the same identical software procedures. The initial time of the figure is taken on August 7th. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. Analogous results were obtained for the DAMA/NaI data [11]. See refs. [6, 7].

The annual modulation present at low energy can also be shown by depicting – as a function of the energy – the modulation amplitude, S_m , obtained by maximum likelihood method over the data considering $T = 1$ yr and $t_0 = 152.5$ day, as described in refs. [6, 7]. In Fig. 3 the obtained S_m are shown in each considered energy bin (there $\Delta E = 0.5$ keV). It can be inferred that positive signal is present in the (2–6) keV energy interval, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom. All this confirms the previous analyses.

The method also allows the extraction of the the S_m values for each detector, for each annual cycle and for each energy bin. Thus, following the procedure described in ref. [6], we have also verified that the S_m are statistically well distributed in all the annual cycles and energy bins for each detector [6, 7]. Among further additional tests, the analysis of the modulation amplitudes as a function of the energy separately for the nine inner detectors and the remaining external ones has been carried out; the

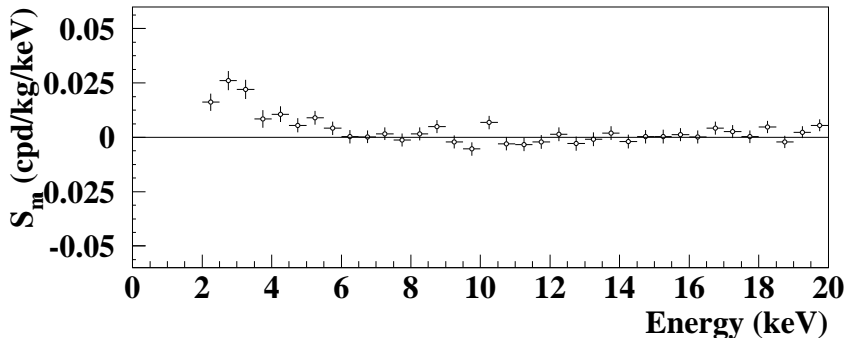


Figure 3: Energy distribution of S_m for the total cumulative exposure 1.17 ton \times yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom. See refs. [6, 7].

values are fully in agreement, showing that the effect is well shared between inner and external detectors [6, 7].

Finally, releasing the assumption of a phase $t_0 = 152.5$ day in the maximum likelihood procedure to evaluate the modulation amplitudes from the data of the 1.17 ton \times yr exposure, one can alternatively write the signal as [6, 7]: $S_{ik} = S_{0,k} + S_{m,k} \cos \omega(t_i - t_0) + Z_{m,k} \sin \omega(t_i - t_0) = S_{0,k} + Y_{m,k} \cos \omega(t_i - t^*)$. For signals induced by DM particles one would expect: i) $Z_{m,k} \sim 0$ (because of the orthogonality between the cosine and the sine functions); ii) $S_{m,k} \simeq Y_{m,k}$; iii) $t^* \simeq t_0 = 152.5$ day. These conditions hold for most of the dark halo models; however, as mentioned above, slight differences can be expected in case of possible contributions from non-thermalized DM components, such as e.g. the SagDEG stream [8] and the caustics [9].

Fig. 4 shows the 2σ contours in the planes (S_m, Z_m) and (Y_m, t^*) for the (2–6) keV and (6–14) keV energy intervals. The best fit values are reported in [7]. Then, forcing to zero the contribution of the cosine function, the Z_m values as function of the energy have also been determined by using the same procedure. The values of Z_m are expected to be zero; by the fact, the χ^2 test supports such a hypothesis [7]. As in the previous analyses, an annual modulation effect is present in the *single-hit* events in the lower energy interval and the phase agrees with that expected for DM induced signals. These results confirm those achieved by other kinds of analyses.

We further stress that sometimes naive statements were put forwards as the fact that in nature several phenomena may show some kind of periodicity. It is worth noting that the point is whether they might mimic the

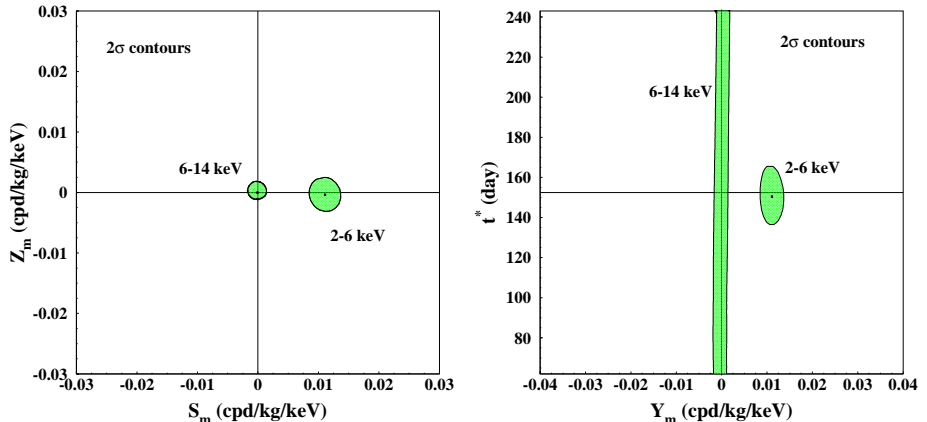


Figure 4: 2σ contours in the plane (S_m, Z_m) (left) and in the plane (Y_m, t^*) (right) for the (2–6) keV and (6–14) keV energy intervals. The contours have been obtained by the maximum likelihood method, considering the cumulative exposure of $1.17 \text{ ton} \times \text{yr}$. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. See refs. [6, 7].

annual modulation signature in DAMA/LIBRA (and former DAMA/NaI), i.e. whether they might be not only quantitatively able to account for the observed modulation amplitude but also able to contemporaneously satisfy all the requirements of the DM annual modulation signature. The same is also for side reactions. This has already been deeply investigated e.g. in ref. [6, 5, 7] and references therein. Some additional arguments have also been recently addressed in [10, 12]. See also later.

No modulation has been found in any possible source of systematics or side reactions for DAMA/LIBRA as well; moreover, no one is able to mimic the signature. Thus, cautious upper limits (90% C.L.) on the possible contributions to the DAMA/LIBRA measured modulation amplitude have been estimated and are summarized e.g. in Table of ref. [6].

Just as an example we recall here the case of muons, whose flux has been reported by the MACRO experiment to have an about 2% modulation with phase around mid-July [13]; recently, also LVD and Borexino results [14, 15] have been reported. We have already demonstrated that not only this effect would give rise in the DAMA set-ups to a quantitatively negligible contribution (see e.g. [6, 7, 16, 11] and refs. therein), but several of the six requirements necessary to mimic the DM annual modulation signature would also fail: e.g. muon would also induce modulation in the *multiple-hit* events and in the whole energy distribution, which is not observed. Moreover, even the pessimistic assumption of whatever hypothetical (even exotic) possible

cosmogenic product – whose decay or de-excitation or whatever else might produce: i) only events at low energy; ii) only *single-hit* events; iii) no sizeable effect in the *multiple-hits* counting rate – cannot give rise to any side process able to mimic the investigated DM signature; in fact, not only this latter hypothetical process would be quantitatively negligible (see e.g. [6, 7] and refs. therein), but in addition its phase would be (much) larger than July 15th, and therefore well different from the one measured by the DAMA experiments and expected by the DM annual modulation signature (\simeq June 2nd). In addition, the phase measured by DAMA experiments in each annual cycle is always around June 2nd, while the muon phase varies from year to year depending on the condition in the atmosphere. In particular, the value (146 ± 7) days [7] measured by DAMA is 5.6σ distant from the LVD mean value ($\simeq 185$ days) and even more from the MACRO one; similar conclusions also hold for Borexino [15]. To be clear, let us note that even a phase value $+3\sigma$ from the one measured for the DAMA observed effect – that is mid-June – cannot match the muon phase unless for one exceptional year; in fact, the maximum outer atmosphere temperature variation (and consequently the atmosphere density variation which causes the muon flux modulation) is typically not in that period at Gran Sasso location. In conclusion, any possible effect from muons is safely excluded on the basis of all the given quantitative facts (and just one of them is enough).

There has been suggested in a recent paper [17] that environmental neutrons (mainly thermal and/or epithermal) once captured by Iodine, might be responsible of the observed modulation through ^{128}I decay, that produces – among others – low energy X-rays/Auger electrons, provided any hypothetical modulation of the neutron impinging the sensitive part of the detectors inside the multi-component multi-ton shield. To be as clear as possible, we skip several comments about that paper and we just summarize few points. Firstly, we stress that – as already quantitatively discussed e.g. in [16, 11, 6, 7] – environmental neutrons cannot give any significant contribution to the annual modulation measured by the DAMA experiments³ and that ^{128}I – if any – cannot mimic the DM annual modulation signature since some of its peculiarities would fail. Moreover, when the ^{128}I decays in the EC channel, it produces low energy X-rays and Auger electrons, but –

³For completeness, we also recall that the experimental set-ups, located deep underground, were equipped with a neutron shield made by Cd foils and polyethylene/paraffin moderator; moreover, a $\simeq 1$ m concrete almost completely surrounds the installation acting as a further neutron moderator. The effectiveness of this shield has also been demonstrated e.g. in ref. [6] where a reduction larger than one order of magnitude has been measured for the thermal neutrons.

since the ^{128}I would be inside the NaI(Tl) detectors – the detectors would measure the total energy release of all the X-rays and Auger electrons emitted following the EC, that is the atomic binding energy either of the K shell (32 keV) or of the L shells (4.3 to 5 keV) of the ^{128}Te . The probability that so low-energy gamma's and electrons would escape a detector is very small; thus, we can conclude that: 1) the L -shell contribution would be a gaussian centered around 4.5 keV; but this is excluded by the DAMA data (see Fig. 3). Moreover, the efficiencies to detect an event per one ^{128}I decay are: 2×10^{-3} , 6×10^{-3} , and 2×10^{-3} in (2–4) keV, (4–6) keV and (6–8) keV respectively, as calculated by Montecarlo code. Thus, in addition, the contribution of ^{128}I in the (2–4) keV – if any – would be similar to the one in the (6–8) keV, while the data exclude that; 2) the K -shell contribution (around 30 keV) must be 8 times larger than that of L -shell, while no modulation has been observed above 6 keV and, in particular, around 30 keV; 3) the ^{128}I also decays by β^- with much larger branching ratio than EC and with β^- end-point energy at 2 MeV. Again, no modulation has instead been observed in DAMA experiments at high energy [6, 7]. Moreover, the data collected by DAMA/LIBRA allow the determination of the possible presence of ^{128}I in the detectors. In fact, neutrons would generate ^{128}I homogeneously distributed in the NaI(Tl) detectors; therefore studying the characteristic radiation of ^{128}I decay and comparing it with the experimental data, one can obtain the possible ^{128}I concentration. The most sensitive way to perform such a measurement is to study the possible presence of the 32 keV peak (K -shell contribution) in the region around 30 keV. This has already been done by DAMA – for other purposes – in ref. [18], where there is also no evidence of such a peak in the DAMA/LIBRA data; hence an upper limit on the area of a peak around 32 keV can be derived to be: 0.074 cpd/kg (90% CL) [18]. Considering the branching ratio of the process and the related efficiency, one can obtain a limit on possible activity of ^{128}I : $< 14.8\mu\text{Bq/kg}$ (90% CL). This upper limit allows to derive the maximum expected counting rate from ^{128}I (see Fig. 5–*Top*), showing that in every case its contribution – if any – is negligible. The contribution is also negligible even in the hypothetical case that the neutron flux had a 10% time modulation with the same phase, period as a DM signal; in fact, even in such a case the contribution to S_m is $< 3 \times 10^{-4}$ cpd/kg/keV at low energy (see Fig. 5–*Bottom*), that is $< 2\%$ of the DAMA observed modulation amplitudes. Therefore, for all the given arguments (and just one of them is enough), no role is played by ^{128}I .

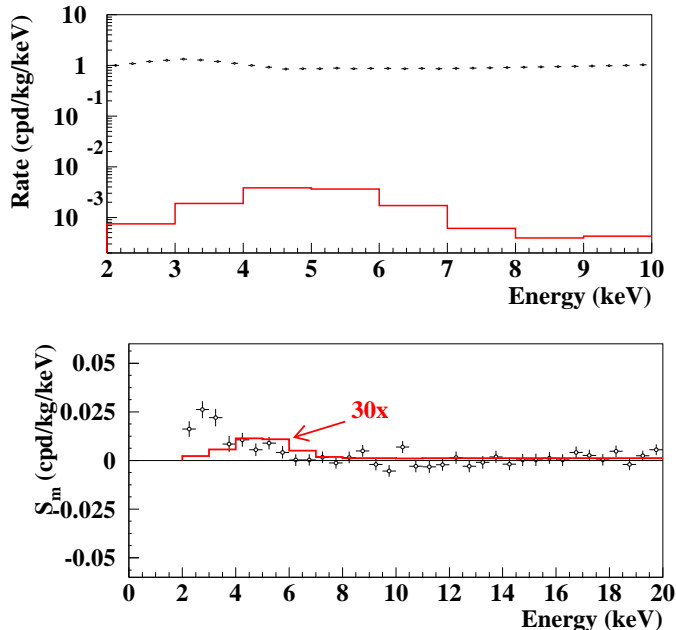


Figure 5: *Top* - Data points: cumulative low-energy distribution of the *single-hit* scintillation events measured by DAMA/LIBRA [5] above the 2 keV energy threshold of the experiment. Histogram (color online): maximum expected counting rate from ^{128}I decays corresponding to the measured upper limit on ^{128}I activity in the NaI(Tl) detectors: $<14.8 \mu\text{Bq/kg}$ (90% C.L.); see the data in ref. [18] and the text. *Bottom* - Data points: the DAMA measured modulation amplitude as a function of the energy. Histogram (color online): maximum expected modulation amplitude multiplied by a factor 30 as a function of the energy from ^{128}I decays corresponding to the measured upper limit on ^{128}I activity given above and assuming the hypothetical case that the neutron flux had a 10% time modulation with the same phase, period as a DM signal. Therefore, the contribution from ^{128}I is negligible and cannot mimic the S_m behaviour; in addition, it is worth noting that ^{128}I never could mimic the DM annual modulation signature since some of its peculiarities would fail (e.g. ^{128}I would induce modulation also in other energy regions, which is not observed). See text.

3 Conclusions

As regards the corollary investigation on the nature of the DM candidate particle(s) and related astrophysical, nuclear and particle physics scenarios, it has been shown that the obtained model independent evidence can be compatible with a wide set of possibilities as discussed e.g. in refs. [16, 11, 8, 19, 20, 21, 22, 23, 24], in the Appendix of ref. [6] and in literature (as e.g. [25], etc.); other possibilities are open. Moreover, as regards possible comparisons with direct, indirect and accelerators activities

see e.g. discussions in [7, 6, 16, 26, 12, 27], etc.. Here we just recall that no other experiment exists, whose result can be directly compared in a model-independent way with those by DAMA/NaI and DAMA/LIBRA.

In conclusion, the six annual cycles of DAMA/LIBRA have further confirmed the peculiar annual modulation of the *single-hit* events in the (2–6) keV energy region. The total exposure by the former DAMA/NaI and the present DAMA/LIBRA is $1.17 \text{ ton} \times \text{yr}$ and the confidence level for the observed effect is cumulatively about 9σ CL. The data satisfy all the many requirements of the signature and no systematics or side reactions able to mimic it (that is, able to account for the measured modulation amplitude and to simultaneously satisfy all the peculiarities of the signature) have been found or suggested by anyone over more than a decade.

In near future new PMTs with higher quantum efficiency will be installed in order to lower the 2 keV energy threshold, increasing the experimental sensitivity and improving the corollary information on the nature of the DM candidate particle(s) and on the various related astrophysical, nuclear and particle physics scenarios. Moreover, it will also allow the investigation of other DM features, of second order effects and of several rare processes other than DM. A third generation R&D effort towards a possible NaI(Tl) ton set-up, DAMA proposed in 1996, has been funded by I.N.F.N. and is in progress.

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